A scalable design procedure for the assessment of the solar energy share in office building façades

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This paper deals with the development of a simulation based predesign procedure for the performance assessment of multifunctional solar-active façades, combined with a hybrid energy system used both for heating and cooling office buildings.

Concentrating parabolic (CPC) solar-thermal collectors and double-glass photovoltaic (PV) panels have been considered for the integration onto a metal glass façade module.

The simulation procedure has been applied to the energetic and economic evaluation of different solar-active façade patterns for three European reference locations.

Keywords: BIST; BIPV; Trnsys; façade design; energy efficiency

Introduction

Figure 1. View of the building-integrated CPC solar-thermal collectors (left, source Frener&Reifer) and double-glass PV modules.

During the last years, the integration of solar renewables within building energy concepts through the installation of Building Integrated Solar Technologies (BISTs) has gained the attention of architects and manufacturers (IEA, 2009; Munari-Probst, 2009). A technological trend has been established which moves towards a multi-functional façade concept where bearing, insulation, water-proofing and sound protection are solved. Thanks to the development of pre-manufactured modular building elements, solar energy conversion technologies can be further integrated.

The energy potential of a BIST is significantly influenced by the local weather conditions, the magnitude of building loads and system driving temperatures and therefore in order to investigate the mutual effect between renewable energy generation systems and building loads, an integrated simulation is needed. Since numerical simulations are in general time-consuming and costly activities, simplified tools can support designers during decision making phases and be used for deriving well-founded performance figures of final energy consumptions.

The paper is divided into the three main parts. In the first part, the description of the simulation based procedure is reported presenting the development of the numerical model of building integrated solar technologies. Then the procedure has been applied to the energetic and economic evaluation of CPC and PV building integrated collectors in different European reference locations. A whole energy concept has been developed together with a dedicated optimized control strategy. Lastly, the conclusions summarize the exploitation potential of solar-active facades and the lessons learned from the energetic and economic analysis.

Description of the procedure

The simulation based procedure has been conceived for the development of a simplified tool to use during preliminary design phases. It is based on a large database including the simulation results of different façade variants and patterns for different orientations and weather conditions. Because of the great amount of combinations, the definition of a systematic and modular simulation approach has significantly eased the work.

The predesign tool has an interface – developed by Frener & Reifer – for visually interacting with the user. It starts with a representation of a blank office façade. The designer can select different variants of solar technologies and creates his/her own façade pattern. The decision making process is based not only on aesthetic motivations but also on energetic figures of the final energy savings potential and economic indicators with respect a traditional office façade that the tool returns as output.

Numerical modelling of building integrated solar-active facades

The integrated simulation of building and energy systems starts from the agreement on simulation boundary conditions and the calculation of relative building loads. The following steps can be identified:

(1) The definition of simulation boundary conditions consisting in:
    (a) the selection of reference locations and of the relative weather file for simulation;
    (b) the description of the reference building geometry, building envelope characteristics and occupants behaviour;
    (c) the identification of indoor air temperature setpoints for guaranteeing adequate comfort levels.

(2) The development of a building integrated numerical model of a solar-active technology. Particular care should be given in treating direct (i.e. beam solar radiation from outside) and indirect (i.e. radiative gains from the rear side of PV module) heat transfers into the conditioned zone.

(3) The calculation of heating and cooling (H&C) demands and power loads for each solar-active façade variants for different orientations.

Because of the potentially high computational effort, the energy analysis of high-rise buildings by means of transient simulations needs adequate simplifications in the development of a geometric model. A usual consolidated assumption states that the energy performance of a high-rise building can be extended from the energy performance of a reference story (typically mid-floors). Additionally, this can be assimilated to the energy behavior of a series of reference office cells oriented according to building exposures. This permits a good trade-off between accuracy of the model and computational time savings.

As previously reported, the presence of a building integrated solar technology has an impact on heat transfer mechanisms. With regards to the short-wave radiation, building integrated solar technologies behave like fixed external shadings. A reduction of solar gains entering in the office space is consequently expected, but this is not equally proportional with the façade transparent ratio (f_w) for direct and diffuse radiation components. Additional to this, a fraction of the absorbed solar radiation in the outer façade is transformed into long-wave radiation because of the presence of intrinsic heat losses. This phenomenon is particularly important in the case of BIPV, because it influences the air cavity temperature as well as the radiative gains on office external surface (see Figure 2). These fluxes are proportional to the difference of the fourth-power surface temperatures. The magnitude of long-wave fluxes depends on collector rear surface temperature and therefore the significance differs from one solar technology to another.

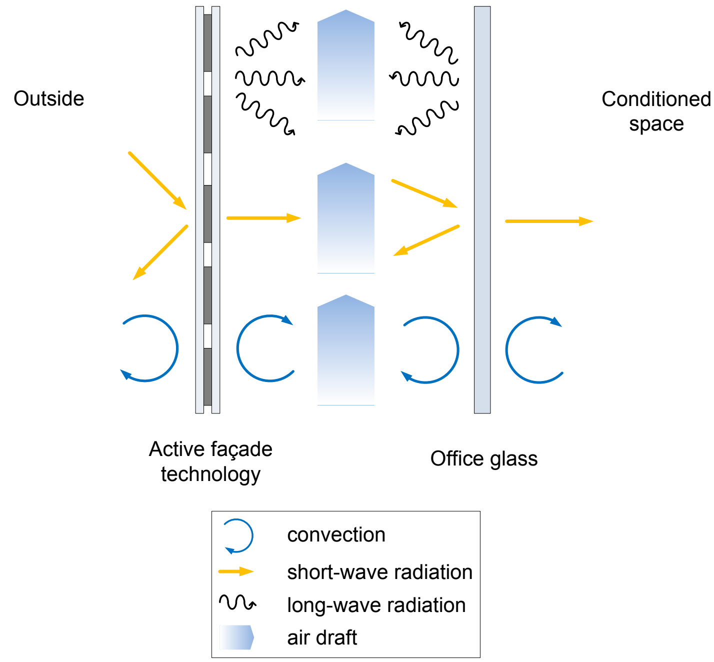


Figure 2. Main heat transfer mechanisms in a building integrated solar façade.

In order to take into account the thermal and optical heterogeneity of solar-active surfaces, the definition of a "fictive" glass pane has been undertaken. This fictive glass pane consists in a superposition of a transparent (glass material for BIPVs; voids for BISTs) and an opaque (PV cell for BIPV; CPC reflector for BIST) layer. The consequent optical characteristics have been calculated for different incidence angle values (from 0° to 90°) by averaging the respective values of opaque and transparent layers according to the transparent ratio f_w, as follows for the solar absorptance:

$$\alpha_j^* = \alpha_{opaque,j} \cdot (1 - f_w) + \alpha_{transp,j} \cdot f_w \quad \forall \; j = 0°,...,90° \tag{1}$$

The so-derived optical characteristics are then implemented into Trnsys window library and used for a comprehensive numerical simulation.

In the case of BIPV, the efficiency of the PV module η_{PV} is a function of the cell temperature T_{PV}, the incident radiation I_g and the rated module efficiency $\eta_{PV,ref}$ given at standard test conditions STC ($T_{PV,ref}$, $I_{g,ref}$).

$$\eta_{PV} = \left(1 + f_{PV,T}\left(T_{PV} - T_{PV,ref}\right)\right)\left(1 + f_{PV,I}\left(I_g - I_{g,ref}\right)\right)\eta_{PV,ref} \quad (2)$$

The CPC performance has been simulated through an efficiency curve function (Duffie & Beckman, 2006) of the difference ΔT between the average fluid and ambient temperature, the incident solar radiation I_g and collector efficiency parameters (a_0, a_1, a_2). The performance characteristics have been derived from manufacturer data-sheet.

Dimensioning of energy systems

Solar thermal heat can be exploited for directly (i.e. direct space heating) or indirectly (i.e. used for cooling purposes by means of a sorption chiller) covering building loads throughout the year. In general terms, the potential of doing this is tied to the solar availability of a given location and the magnitude of the different building loads.

In the case of Solar Combi+ systems (IEE, 2009), several aspect ratios are typically used for dimensioning main system components such as the ratio f_{TES} between the capacity of the thermal energy storage (TES) and the surface of solar-thermal collectors and the maximum chilling capacity per collector area f_{sorp}. Typically values for f_{TES} of 0.025-0.075 m^3/m^2 and for f_{sorp} of 2-5 m^2/kW_{ch} are a good dimensioning criterion.

The adoption of solar-driven working modes is a function of the solar collected energy solar and therefore because of the its intrinsic unpredictability, there is the need of considering back-up systems for heating, cooling and hot water preparation.

In tertiary buildings, the electrical loads are generally much greater than the energy delivered by the photovoltaic system. Therefore, there is not the risk of over-dimensioning since all the generated energy will be consumed by the building usage.

Application to real case scenarios

Simulation boundary conditions

The presented procedure has been applied to the evaluation of solar-active facades variants in tertiary building applications for three reference European locations (Frankfurt in Germany, Bolzano and Rome in Italy). These locations are representative of a good range of European climates. Rome has a mild Mediterranean condition and it is usually taken as a reference Italian climate, whereas Frankfurt is a good reference for a central Europe context. Both locations have also a good potential of constructing high-rise buildings, because they are the seat of international institutions and commercial enterprises.

The simulation has been conducted by defining a reference thermal zone with a gross floor area of 31.5 m^2 and a volume 94.5 m^3 (Figure 3). It is modelled in a way that only a single surface is exposed outdoors while the others are assumed to be adiabatic. The façade is assumed to be composed by three modules with length of 1.75 m onto which the solar active technologies have been placed. As a reference base scenario, a gross fenestration ratio of 100% has been chosen. This value has been then reduced to 60% in order to show the dependency of solar-active technologies to building loads.

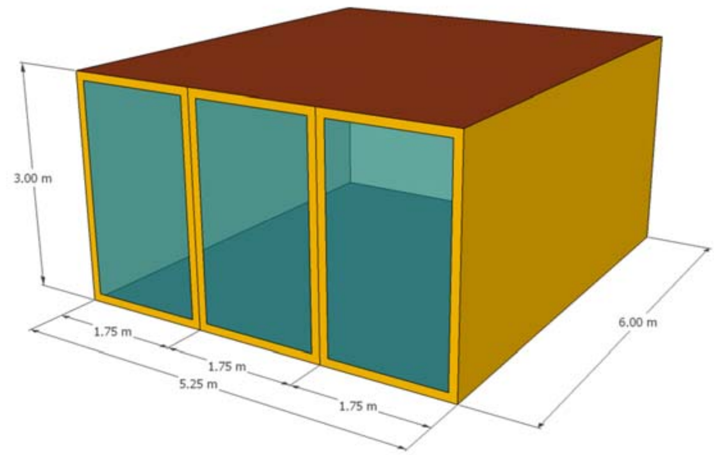


Figure 3. View of the reference office zone.

A single office floor is defined by juxtaposing the single reference zones in a way that the final office plant has a rectangular shape and the solar-active technologies are installed only in one façade orientation that varies between from East to West. As a reference façade configuration, a fully glazed zone is considered. The façade design considers different façade patterns in a way that the area of solar-thermal and photovoltaic technologies has been varied from 0% to 100% with a step of 20%.

$$A_{ST} + A_{PV} + A_{ref} = A_{tot} \tag{3}$$

$$\xi_{ST} = A_{ST} / A_{tot} \tag{4}$$

$$\xi_{PV} = A_{PV} / A_{tot} \tag{5}$$

The boundary conditions listed in Table 1 have been used for running the simulation on the reference office zone. The internal walls are light-weight assemblies whereas the ceiling and the floor have are made by 35 cm of concrete, 12 cm of screed and a finishing carpet layer. Space heating and cooling loads are met by supplying heating and cooling water through a low-temperature radiant floor system. The inlet fluid set point temperatures $T_{f,in}$ for radiant heating and cooling have been fixed to 30°C and 15°C, respectively, whereas the mass flow rate m_{sp} amounted to a constant value of 7 kg/h/m^2. The fluid is circulated through the radiant system for meeting comfort conditions during occupation time. In order to do this, a lower and an upper limit of 20°C and 26°C for indoor air temperature have been defined, respectively. The efficiency parameters of PV and CPC collectors have been listed in Table 2 and Table 3.

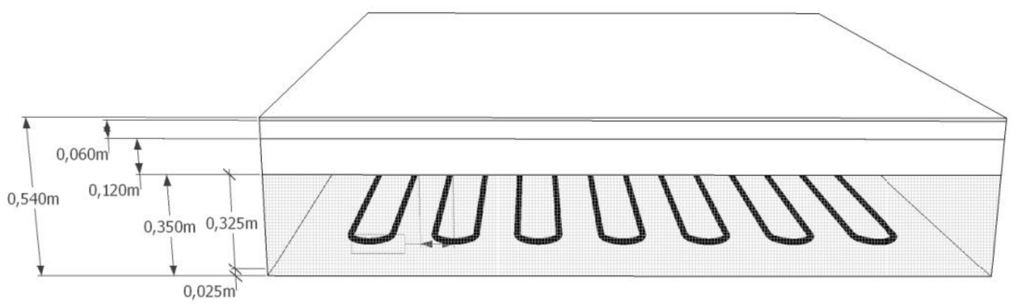


Figure 4. View of the radiant energy distribution system and floor assembly.

Table 1. Simulation boundary conditions.

Boundary conditions	**Description**
Occupancy	Max. occupancy: 2 persons present from 8:30 to 12:3 and from 13:30 to 17:30 from Monday to Friday, with a summer and winter week leave Sensible gain: 60 W/person (30% radiative, 70% convective) Latent gain: 0.059 kg/h/person
Appliances	2 laptops (70 W/unit), 1 printer (50 W/unit)
Lighting	Halogen lighting fixtures guaranteeing 500 lux on working planes, specific gains equal to 10 W/m^2 with 60% convective

	fraction
Ventilation and infiltration	Fresh air supply of 39.6 m^3/h/person Building leakages of 0.15 ach
Shadings	Internal sunscreen operated by the users according to the indoor temperature. No external shadings are considered as well as the influence of urban or environmental context.

Table 2. Performance parameters of PV modules at reference STC.

Material	**$\eta_{PV,ref}$, [-]**	**$f_{PV,T}$, [-]**	**$f_{PV,I}$, [-]**
Polycrystalline	0.135	-0.0045	0
Amorphous	0.060	-0.0025	0

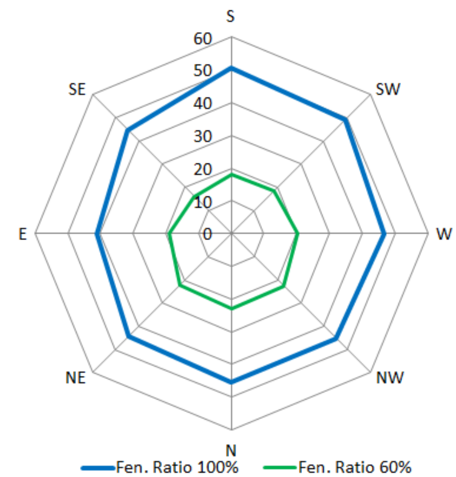
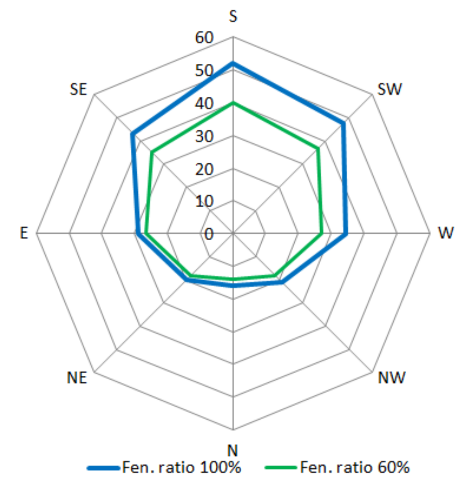
Table 3. Thermal performance parameters of CPC collector.

	A_{coll} [m^2]	**a_0 [-]**	**a_1 [W/(m^{2}K)]**	**a_2 [W/(m^{2}K^2)]**	**C_{eff} [kJ/(m^{2}K)]**
CPC solar collectors	4.74	0.457	0.699	0.003	7.96

Building energy demands

In Table 4 specific heating and cooling energy demands have been plotted for different façade orientations and for a fenestration ratio f_w of 100% and 60%. It is clear as a reduction of the glazed façade mainly influences heating and cooling demand. As average a reduction in the case of heating and cooling between 56% and 70% and between 12% and 16% is noticed, respectively., respectively. No relevant changes in terms of heating and cooling load powers for different façade orientations and the average maximum cooling and heating peak amount to 70 W/m^2 and 83 W/m^2, respectively.

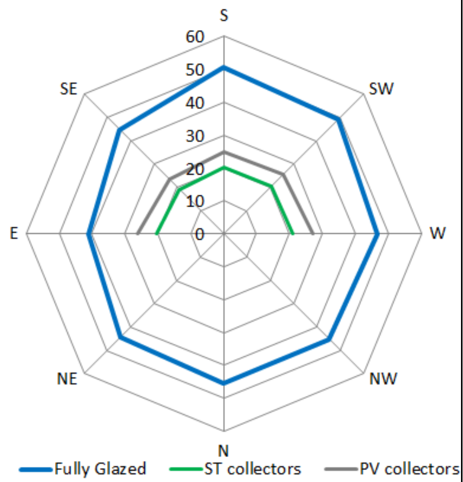
Table 4. Specific heating adn cooling demands of the reference office zone for fenestratio ratio of 100% and 60%.

Location	**Specific heating demand Q_{heat}, [kWh/(m²y)]**	**Specific cooling demand Q_{cool}, [kWh/(m²y)]**
Bolzano		

Additionally, a comparison among the behaviour of the reference fully glazed façade, the solar-thermal (ST) and photovoltaic (PV) variants are shown for the locations of Frankfurt, Bolzano and Rome. In terms of heating demand a reduction between 42% and 58% is induced by double-glass PV modules and between 57% and 69% by the CPC solar collectors. Cooling demands are evenly reduced between 15% and 34% by double-glass PV modules and between 39% and 53% by the CPC solar collectors. This reduction is similarly appreciated among the three locations. On the other hand no significant change in terms of heating and cooling power is noted.

Table 5. Influence of the integration of solar-facade technologies on heating/cooling energy demands and loads in the location of Bolzano.

Location	**Specific heating demand Q_{heat}, [kWh/(m²y)]**	**Specific cooling demand Q_{cool}, [kWh/(m²y)]**

<table>
<tr>
<td>Bolzano</td>
<td>
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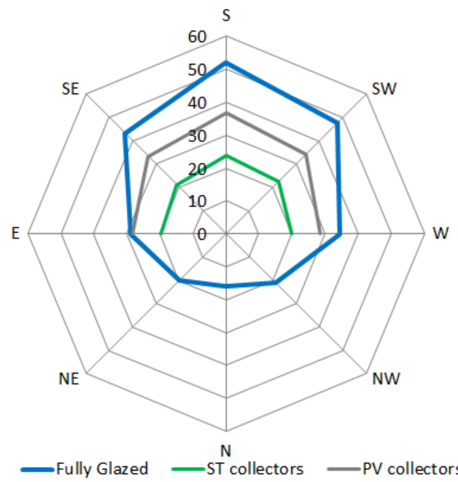
<td>
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Description of the energy concept

The energy concept of the plant layout aims to on the one hand to minimize the final energy consumption throughout the year and on the other hand to optimize the exploitation of the solar-thermal energy collected by the CPC collector for covering space heating, space cooling and hot water production. In order to meet this target, a hybrid energy system and a dedicated control strategy have been developed through the integration of a compression heat pump and an adsorption chiller technology (see Figure 5). Hybrid systems are defined as those systems that provide heating, cooling and hot water through the combination of two or more energy sources into a single system, therefore overcoming the limitations of individual technologies. Because of the number of system components, control strategy is key in the management of energy flows and therefore a dedicated control strategy has been further development.

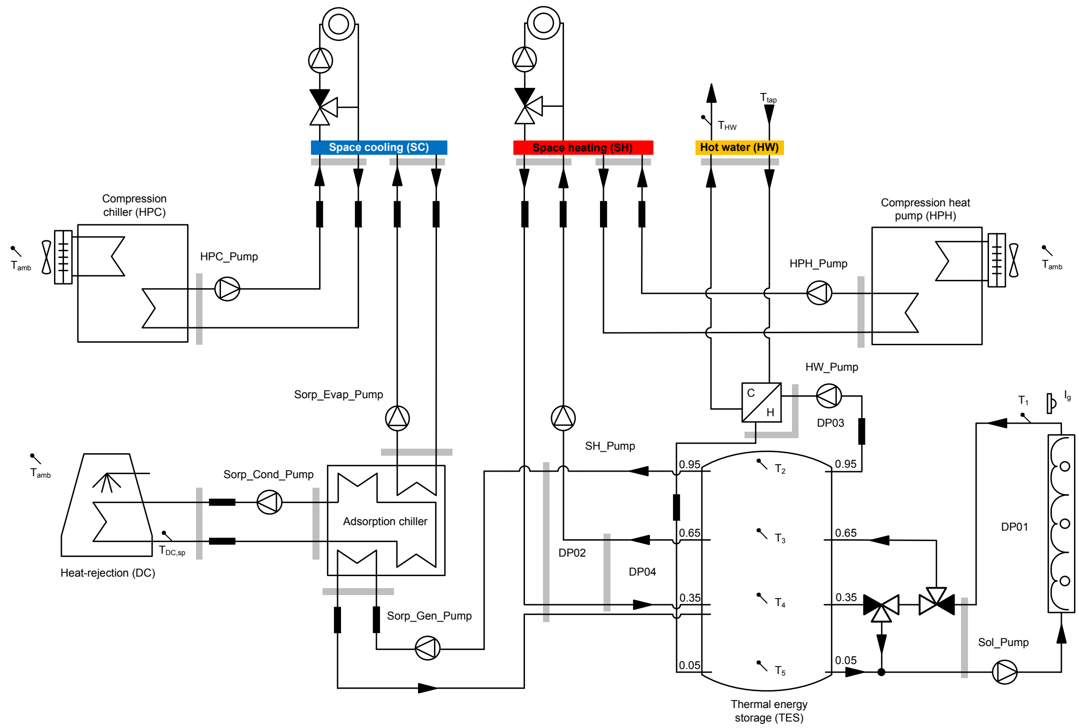


Figure 5. Layout of the hybrid energy system.

As previously mentioned, heating and cooling loads are covered through the use of radiant concrete ceilings. The secondary circuit is divided by the primary side by placing a hydraulic junction. From here a number of heating and cooling secondary circuits are considered as many as the conditioned zones. The activation of H&C schemes is controlled by imposing a minimum set point temperature in each hydraulic junction.

For both heating and cooling schemes, two options are available. The priority is given to solar-thermally driven schemes, whereas electrically-driven schemes are used as backup alternatives. The activation of solar-thermally driven cooling schemes occurs when a minimum temperature of 65°C is available in the solar storage. If this condition is not met, the compression chiller is then activated. Direct solar heating is accomplished by delivering the collected heat through the radiant system. When these criteria are not met, ambient air-source compression heat pump is then activated.

As previously said the capacity of the sorption chiller and TES volume is a function of the surface of solar-thermal collectors. Because of the non-optimal installation of the solar field, a greater value with respect to those mentioned in the previous section has been used (f_{sorp}=7 m^2/kW_{ch} and f_{TES}=0.03 m^3/m^2).

A photovoltaic power generation system is additionally considered. Since building-integrated photovoltaic (BIPV) modules are a variant of façade design, solar energy can be further converted into electric energy and according to the needs dispatched into the national grid or directly use for covering office loads. The interaction between the thermal and electrical plant layout is limited in the post-processing phase where a net-zero energy building analysis has been performed.

Performance indicators

In order to quantify the performance of the hybrid system supplied by the collected energy of the solar-active facade, a series of performance figures have been defined.

- **Seasonal Performance Factor, SPF**. It indicates the amount of electric energy required for covering a building load divided the building load. The electrical energy computes the electrical energy consumption of each single system component (chiller, compression heat pump, pumps). Concisely, SPF gives a measure of the goodness of how electrical energy is spent for covering building loads.

$$SPF_{el,j} = \frac{Q_j}{W_{el,j}} \quad (6)$$

- **Final Energy, FE**. It is the amount of the energy consumed by the system for covering the building loads. Since in this case electricity is the main energy carrier, final energy corresponds to the total electrical energy consumption W_{el}.

- **Solar Fraction, SF**. It computes the ratio between the fraction of the j load covered through a solar thermally driven scheme $Q_{j,sol}$ and the entire load Q_j or in other works it gives a measure of the exploitation of solar energy for covering direct/indirectly building loads.

$$SF_j = \frac{Q_{j,sol}}{Q_j} \tag{7}$$

- **Load matching index, $f_{el,load}$**. In order to quantify the balance between the delivered $W_{el,del}$ and the purchased electrical energy, an hourly calculation (τ = 1 hour) should be performed thought the year according to Sartori et al. (2011):

$$f_{el,load} = \frac{1}{N}\sum_{year} \min\left[1, \frac{W_{el,del}(\tau)}{W_{el,load}(\tau)}\right] \tag{8}$$

Simulation results

A set of parametric simulations has been carried out for different solar façade orientations (5 orientations from East to West) and different façade patterns with a variable percentage of PV or ST technologies (ξ_{ST}, ξ_{PV}). In order to show the great amount of combinations, the variability range of the different performance indicators has been graphed by means of contours.

Exploitation of solar energy

As regard as the heating demand, the solar fraction SF_{heat} reaches a maximum value of 12-14% for Bolzano and Frankfurt (Figure 6), whereas for Rome a share of 24% (Figure 8) has verified mainly because of the limited heating demand than the great amount of solar energy available. The reduction of the fenestration ratio from 100% to 60% is decisive for increasing the SF_{heat} up to 17-18% and 39% for Bolzano-Frankfurt and Rome, respectively.

Cooling demand is covered by 13-14% through solar-activated working schemes in Bolzano and Rome (Figure 9). In Frankfurt this value reaches 20%, because of the greater latitude and the consequent lower sun path during the summer season (Figure 7). A lower fenestration ratio (60%) is again positively influencing the share of cooling loads for all three locations reaching a value 23%, 16% and 14% for the locations of Frankfurt, Bolzano and Rome, respectively.

The share of hot water production is great because of the limited demand (1.2 kWh/m^{2}y) even for low values of ξ_{ST}. In the worst case (Bolzano, ξ_{ST}=20%) a value of 67% is reached. The influence of a lower fenestration ratio is not significantly influencing this figure of merit.

Since ambient air and solar radiation sources are used as alternatives, AF ratios are complementary to SF ratios. So that if the SF increases, the AF necessarily decreases and viceversa.

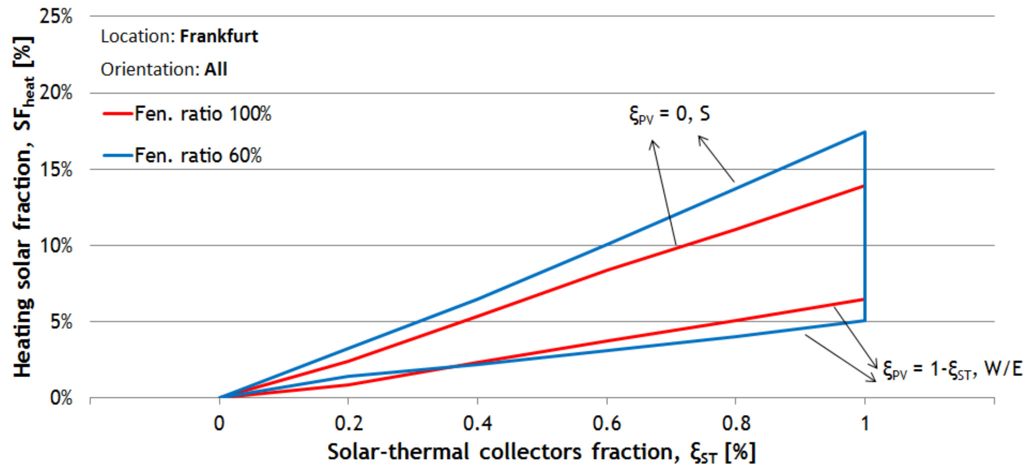


Figure 6. Plot of the SF_{heat} as a function of the fraction of solar-thermal collectors for the location of Frankfurt.

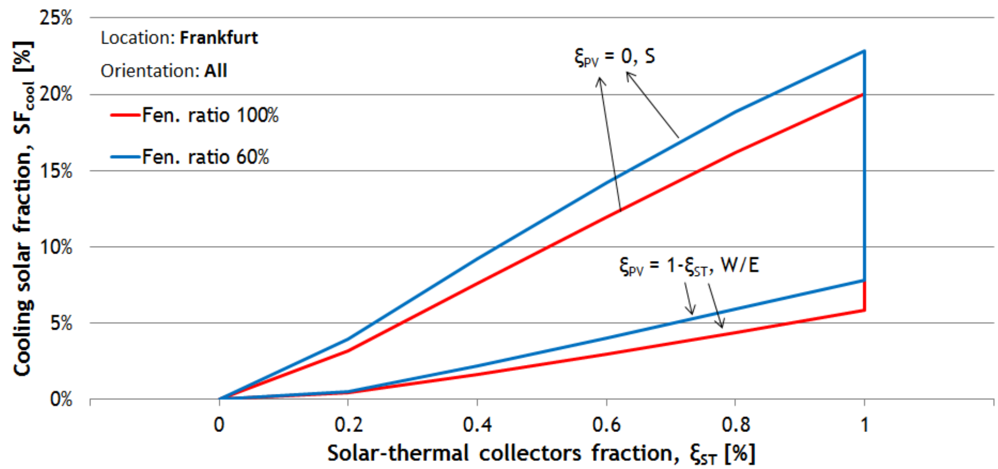


Figure 7. Plot of the SFcool as a function of the fraction of solar-thermal collectors for the location of Frankfurt.

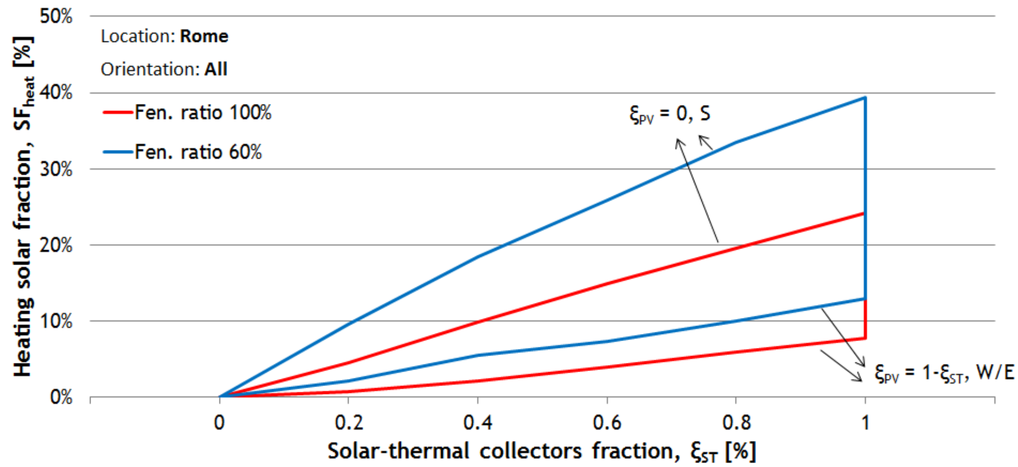


Figure 8. Plot of the SF_{heat} as a function of the fraction of solar-thermal collectors for the location of Rome.

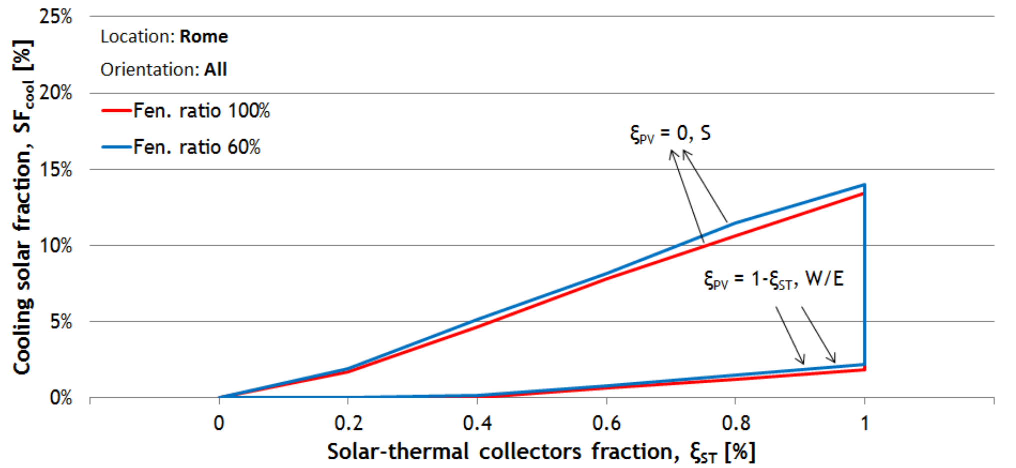


Figure 9. Plot of the SF_{cool} as a function of the fraction of solar-thermal collectors for the location of Rome.

System Seasonal Performance Factor

From Figure 10 to Figure 13 the dependency of SPFs to a variation of solar-thermal collector is plotted. In general it can be affirmed as the integration of solar-thermal collectors in the façade has a net benefit in all locations.

With respect to a reference electrically driven system (or in other words to a façade with a value of ξ_{ST}=0), the $SPF_{el,heat}$ value increases of 13%, 10% and 23% for Frankfurt, Bolzano and Rome, respectively (Figure 10). On equal terms of ξ_{ST} value, a lower fenestration ratio increases this benefit up to 17%, 14% and 50% for the three locations.

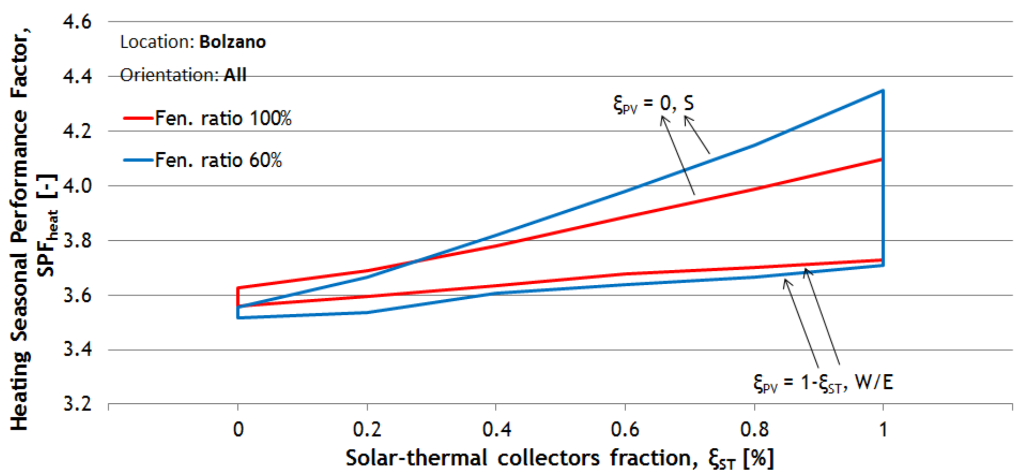


Figure 10. Plot of the SPF_{heat} as a function of the fraction of solar-thermal collectors for the location of Bolzano.

Cooling can further benefit by the presence of solar-thermal collectors the incidence is limited compared to heating loads, reaching a value 5%, 6% and 10% for the locations of Frankfurt, Bolzano (Figure 11) and Rome, respectively. Since a lower fenestration has as major consequence on the reduction of the cooling demand, the performance in covering the load through solar-driven mode becomes more efficient with a net increase of 7% and 13% for the cities of Frankfurt-Bolzano and Rome.

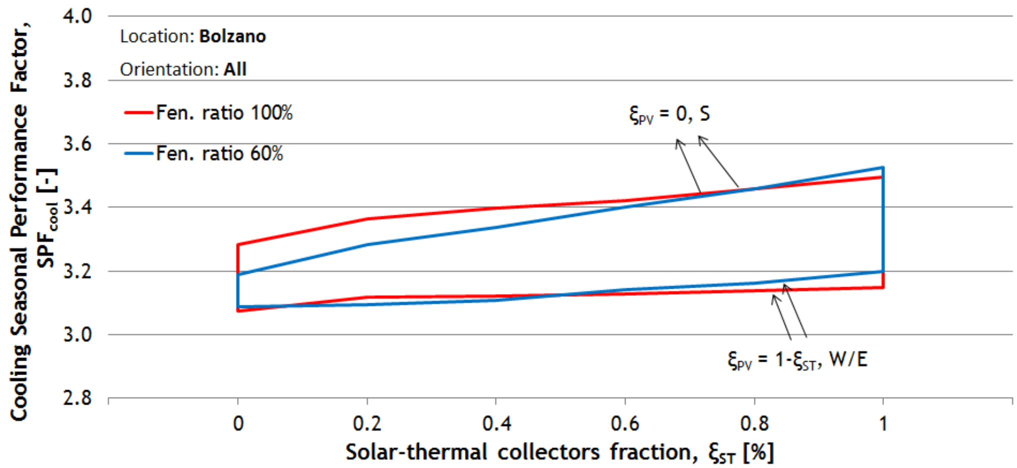


Figure 11. Plot of the SPF_{cool} as a function of the fraction of solar-thermal collectors for the location of Bolzano.

Heating and cooling performances have a repercussion on the total system performance factor $SPF_{el,tot}$. The benefit of solar-thermal collectors with respect to reference electrically driven systems amounts to 18%, 25% and 23% for Frankfurt, Bolzano and Rome, respectively. The relevance of this number can be better understood when it is translated in terms of a reduction of electricity demand and consequently in terms of cost savings. This can be calculated as follows:

$$\%\ \text{Cost} = \left(\frac{1}{SPF_{el,tot}} - \frac{1}{SPF_{el,tot,ref}} \right) \Big/ \frac{1}{SPF_{el,tot,ref}} \quad (9)$$

Therefore for a reference $SPF_{el,tot,ref}$ value of 3.2 for the location Bolzano, the maximum energy reduction when ξ_{ST}=1 can be quantified in 20% (Figure 12).

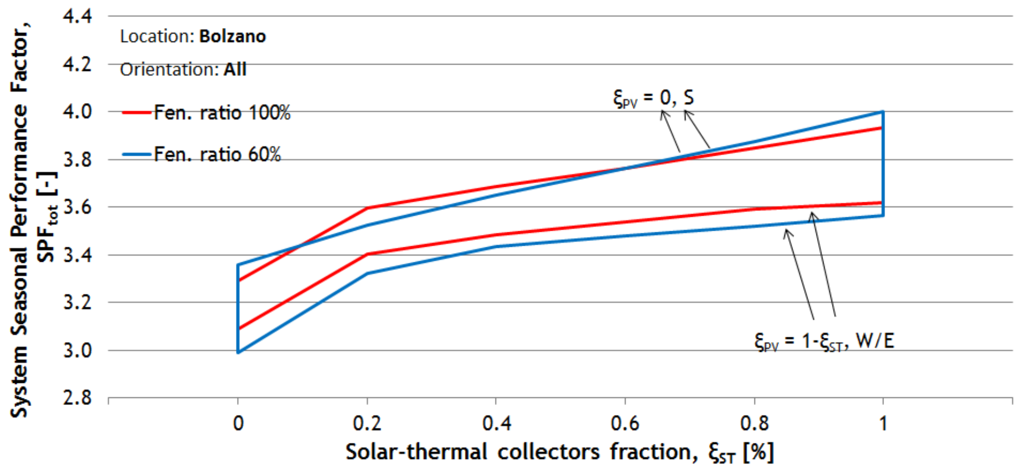


Figure 12. Plot of the SPF_{tot} as a function of the fraction of solar-thermal collectors for the location of Bolzano.

Since the hot water demand for an office is limited compared to typical residential buildings, the influence of the $SPF_{el,HW}$ on the $SPF_{el,tot}$ is limited. Nevertheless an average value of $SPF_{el,HW} = 400$ can be reached when the $\xi_{ST}=1$ is used, whereas it is 0 when obviously $\xi_{ST}=0$.

A similar analysis to the previous one has been carried out investigating the system performance indicators by varying the fraction of photovoltaic collectors installed on the facade (Figure 13). Since photovoltaic collectors are not contributing in the fulfillment of thermal building loads, the system performance is indifferent to a change of ξ_{PV} ratio or in general negatively influenced. This tendency is clearly shown in all three locations.

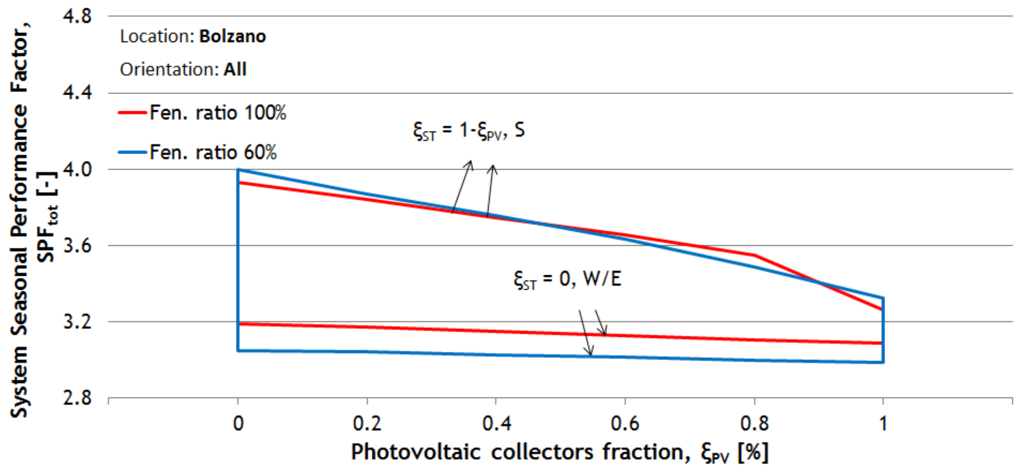


Figure 13. Plot of the SPF_{tot} as a function of the fraction of photovoltaic collectors for the location of Bolzano.

Final Energy consumption

The positive influence due to the presence of solar-thermal collectors on SPF values is reflected in terms of system final energy. This figure is very meaningful since it quantifies the amount of energy (electricity in this case) that has to be purchased by final users.

The final energy consumption of the reference fully-glazed façade without solar-active components amounts to 22.3 kWh/(m^{2}y), 22.5 kWh/(m^{2}y) and 17.2 kWh/(m^{2}y) for the locations of Frankfurt, Bolzano and Rome, respectively (Figure 14 - Figure 16).

The benefit that solar-thermal collectors bring to the system has been quantified in terms of reduction of the final energy up 20-25% as average between the locations here considered. With this regard, the advantage of a façade design with a fenestration ratio of 60% is analogous in relative terms to that of a fully glazed façade.

The presence of façade integrated PV modules does not contribute in the reduction of final energy demand of the building but only in the production of renewable electricity.

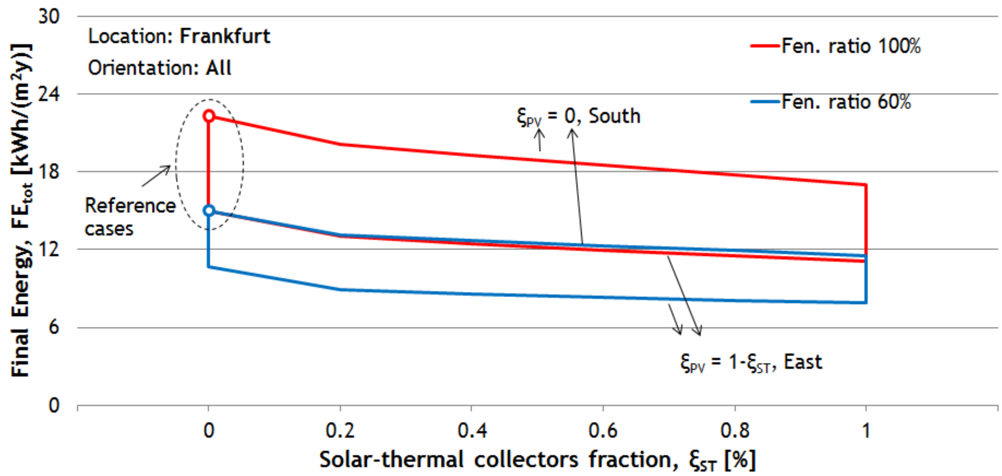


Figure 14. Plot of the FE_{tot} as a function of the fraction of solar-thermal collectors for the location of Frankfurt.

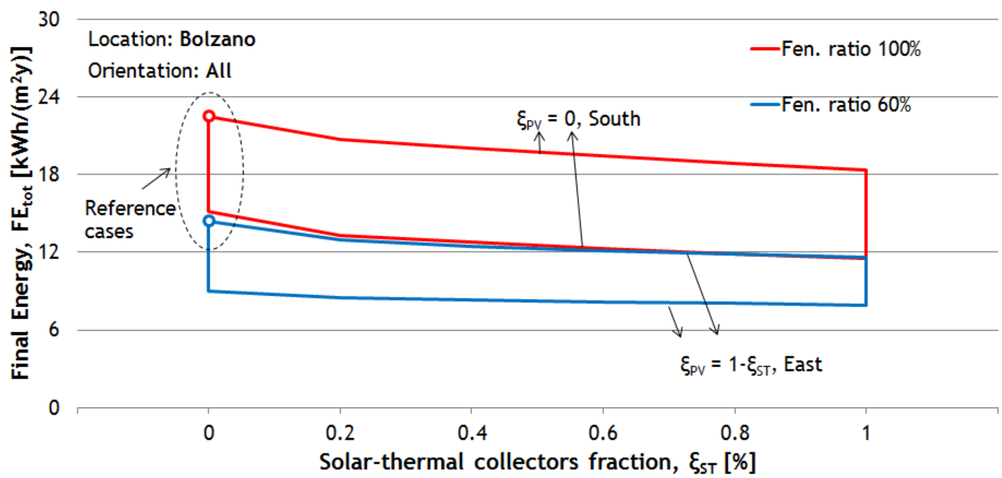


Figure 15. Plot of the FE_{tot} as a function of the fraction of solar-thermal collectors for the location of Bolzano.

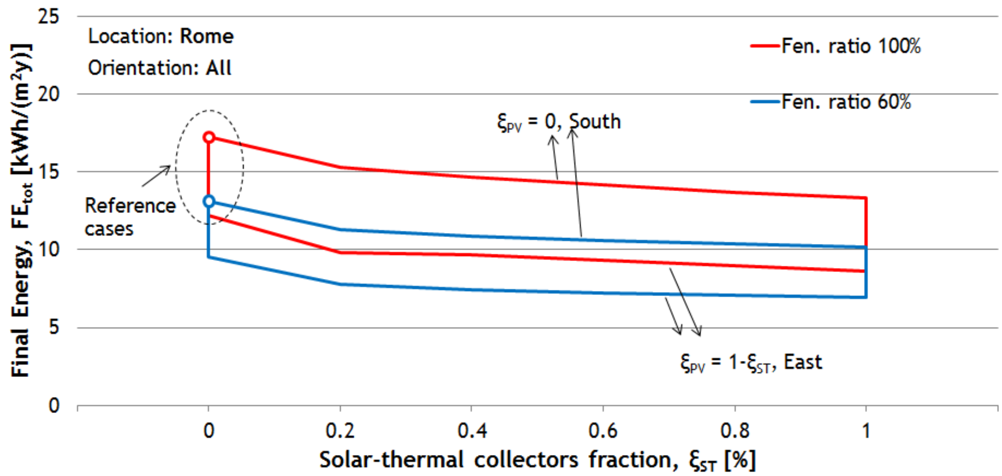


Figure 16. Plot of the FE_{tot} as a function of the fraction of solar-thermal collectors for the location of Rome.

Electrical load matching index

Thanks to the presence of building integrated PV modules the facade can contribute in covering electrical building loads. This contribution is dependant to several parameters such as the PV technology, the facade orientation, the geographic location and clearly the amount of surface.

The load matching index aims to calculate the instantaneous matching between PV energy generation and building load demand. As can be seen in Figure 17, the contribution of PV modules is almost linearly dependent to the total installed capacity the PC technology at any location conditions and it can reach a maximum value of 25-48% for a reference fully glazed façade.

The influence of an eastern/western façade orientation with respect to a South orientation leads to a decrease of -26%, -12% and -9% in terms of load matching index for the Frankfurt, Bolzano and Rome, respectively. With respect to reference polycrystalline cells, amorphous modules have a reduction of 59-62% in terms of load matching index.

Because of the lower façade area, a fenestration ratio of 60% influences proportionally the collected energy and consequently the electrical load matching index. However, the difference between the two cases is compensated in some locations by lower electrical loads so that similar values can be achieved.

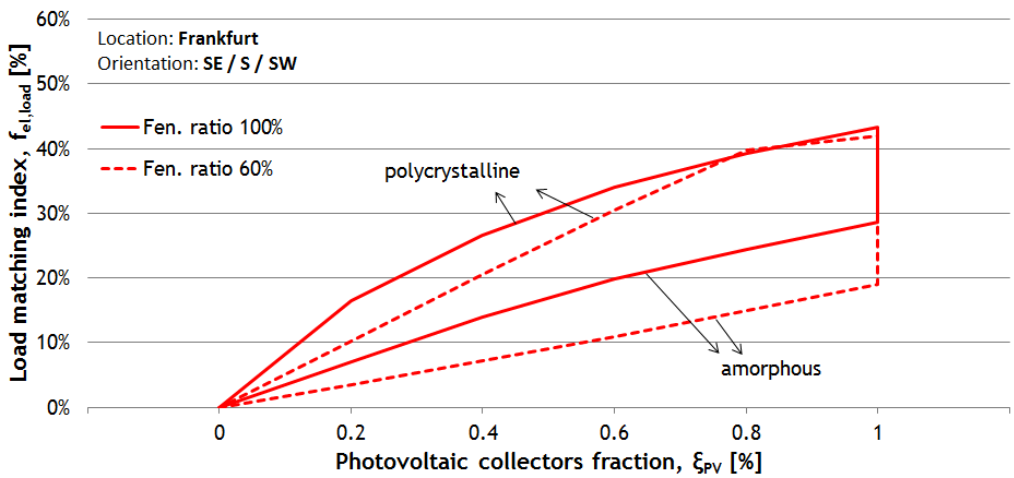


Figure 17. Plot of the load matching index fel,load as a function of the fraction of solar-thermal collectors for the orientation SE/S/SW and the location of Frankfurt.

Economic analysis

In accordance to the approach presented in the simulation sections, the economic analysis of a single floor has been carried out by comparing different façade patterns under the same boundary conditions. The comparison has been made with respect to a reference fully glazed façade (100% fenestration ratio). The analysis has been conducted either by specifying the economic quantities with respect of the conditioned area or with respect of the façade area. Both calculation approaches lead to identical final results.

For sake of simplicity, the economic attractiveness of a given façade pattern has been quantified by calculating the simple return of investment ROI as the ration between:

- The net additional investment costs, calculated as the difference between the investment costs (600 €/m^2 for the reference fully-glazed façade, 1200 €/m^2 for the solar-active PV or ST façade variants) and the incentives (only for the Italian locations according to Decreto Ministeriale 28.12.2012);
- The annual energy savings expressed in terms of final energy reduction (assuming a unitary energy cost of 0.20 €/kWh).

The calculation of the energy savings have been performed by subtracting from the yearly final energy costs of the reference system (system energy performance of a fully glazed façade reference floor) those of a given solar-active façade. Yearly final energy costs range between 1.2 and 4.5 €/m^2 per office floor area (Figure 18), corresponding to final energy savings comprised between 0.6 and 4.0 €/m^2.

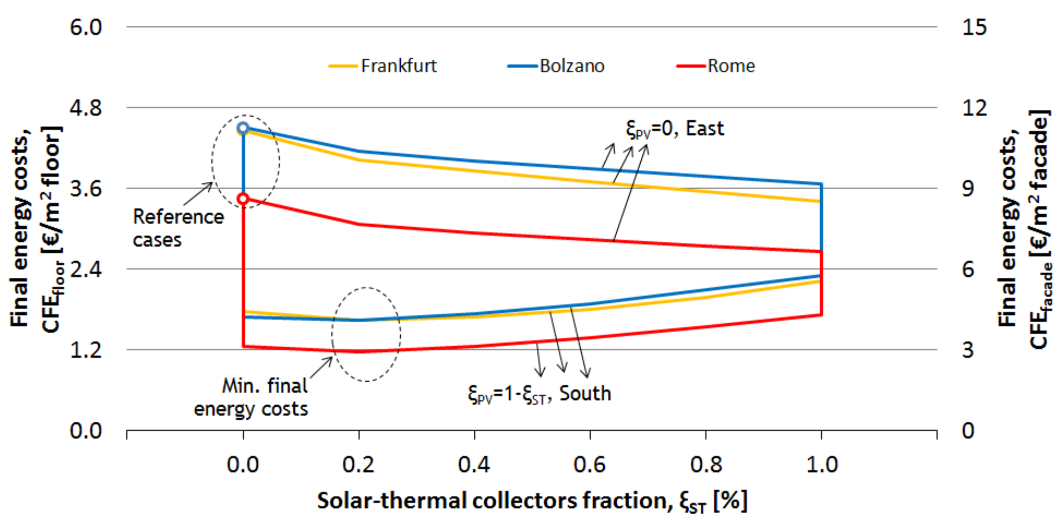


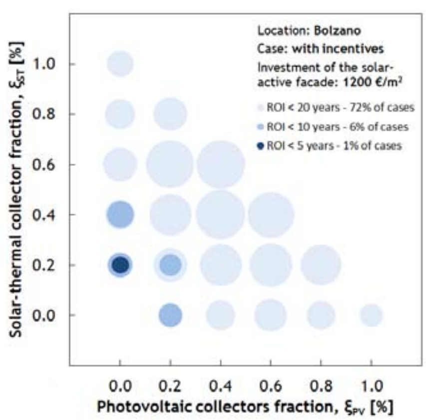
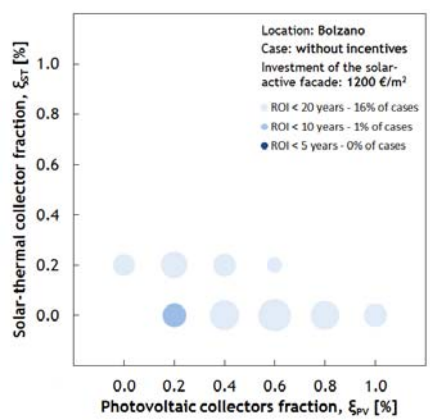
Figure 18. Final energy costs for different façade variants and the location of Frankfurt, Bolzano and Rome. The values are presented as a function of the solar-thermal collectors fraction installed in the solar-active facade. Final energy costs are reported for the office floor area (left y-axis) and the façade area (right y-axis).

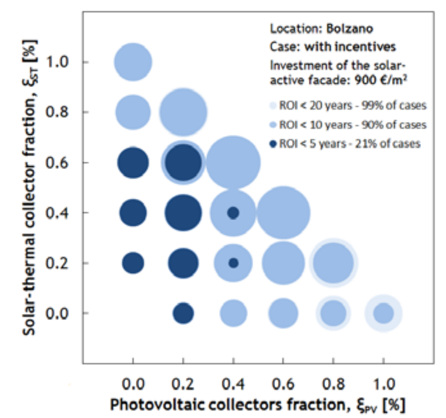
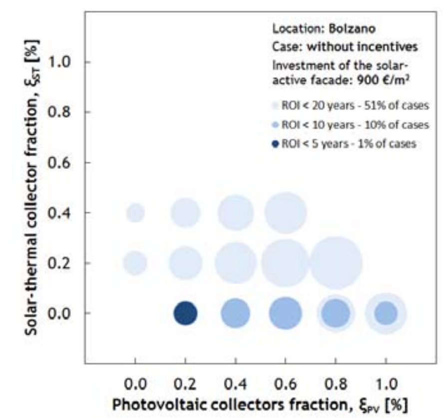
In order to understand the dependency of the economic attractiveness to the façade design, the ROI values of façade variants have been sorted according to the percentage of the installed solar-thermal and photovoltaic collectors (Table 6). The façade design that leads to a ROI value less than 5 years with incentives is characterized by a combination of the 20% of solar-thermal collectors and the 0% of photovoltaic collectors and an orientation of South or South-West. A ROI value comprised between 5 and 10 years is achieved for a solar-thermal and photovoltaic collector fraction less than 40% and 20%, respectively. In this case, the orientation is not crucial since the number of combination is equally distributed from East to West.

If the incentives are not considered in the calculation, the results of the economic analysis change. ROI values less than 5 years can be achieved only in Frankfurt, whereas in Bolzano and Rome ROI values greater than 5 years are only possible. The reduction of the final energy demand determined by the presence of photovoltaic collectors is dominant in this scenario on the presence of solar-thermal collectors. Looking at the Table 6, it can be seen that the highest values of ROI are achieved for a façade design with 20% and 0% of photovoltaic and solar-thermal collectors in all three locations. In the case without incentives, the most effective orientations are still South and South-West.

It has become once again evident that the investment costs are key. When the solar-active façade fraction increases, the increase of the investment cost has a dominant effect on the increase of final energy savings. Therefore the façade design that in general leads to the lowest value of ROI is that characterized by a minimal solar-active façade fraction (ξ_{ST} or ξ_{PV} equal to 20%), because the investment costs are best compensated by final energy savings. In order to further clarify the last sentence, the previous calculation has been repeated assuming an investment cost of 900 €/m^2 (in place of 1200 €/m^2) for both photovoltaic and solar-thermal collector variants (Table 6). The possible configurations with a ROI value less than 5 years are significantly increased with respect to the initial case. For example for the location of Bolzano, the percentage of combinations with a ROI less than 5 years passes from 1% to 21% (with incentives) and from 0% to 1% (without incentives). More interesting is the percentage of cases with a ROI value lower than 10 years: from 6% to 90% (with incentives) and from 1% to 10% (without incentives).

Table 6. Distribution of the ROI value as a function of the solar-thermal and photovoltaic collector fraction for the cases with and without incentives and for the three locations of Bolzano and Rome.

Investment of the solar-active facade	**With incentives**	**Without incentives**
1200 €/m^2		

900 €/m^2		

Conclusions

The simulation based procedure has been developed for conveying since the early design stages well-funded performance figures of the influence of solar-active facades on building final energy consumption and economic considerations consequent to a certain façade design. It has applied for the development a simplified tool for façade designer based on simulation results.

It has been applied to real case scenarios of office façade buildings evaluated for the reference locations of Frankfurt, Bolzano and Rome. Thanks to this an energetic and economic analysis has been carried with respect to a reference office façade and the following conclusions have been derived:

- Building integrated solar-active façades are effective solutions for improving the energy efficiency of a typical reference office in different European locations. They represent an interesting and viable solution for contributing to covering building loads through the adoption of a renewable energy source. In particular the most significant benefit is seen for the cooling demand where a reduction between 15% and 34% by double-glass PV modules and between 39% and 53% by the CPC solar collectors can be achieved. The performance of these systems and the consequent share of building loads covered are extremely sensitive to a change of location and building loads.

- Solar-thermal collectors can significantly contribute to cover heating, cooling and hot-water loads in all the three locations here analyzed. This benefit has been here quantified in +10-50% on SPF_{heat}, +5-13% on SPF_{cool} and +18-30% on SPF_{tot} with respect to traditional electrically driven systems. This is due on the one hand to the lower heating and cooling demand of the office consequent to the solar-active façade, on the other hand to the reduction of the final energy consumption thanks to an effective exploitation of solar energy. This point is mainly motivated by looking at savings in terms of FE_{tot} (quantifiable in -20-26%) between a reference office façade and solar-active façade.
- Photovoltaic collectors permit to produce electric energy consumption and to use it directly to cover the loads of the office. Nevertheless this load matching is limited to 40-45% at the maximum and if higher values are expected or needed roof area and battery use should be considered. Technologies and materials have to be adequately selected accordingly to the orientation (i.e. unlike polycrystalline PV modules, amorphous collectors can work properly also at eastern orientation) and the location.

An economic analysis has investigated the attractiveness of solar-active facades in new building constructions by calculating the return of investment with respect to a reference fully-glazed façade designs. It has emerged that:

- The final energy in absolute terms can range between 1.2-4.5 €/m^2 with respect to the office floor area or 0.6-4.0 €/m^2 with respect to the façade surface area.
- The final energy savings determined by a direct exploitation of solar energy for heating and cooling purposes through the solar-thermal collectors and by a coverage of electric energy though photovoltaic collectors range between 14.8% and 64.9%. The wide range is caused by the location, the solar-façade design and orientation.
- For given solar-active surface area onto the façade, the photovoltaic variant has achieved better ROI values because of the low specific investment cost (made by only the façade module) and the final energy savings determined by the consumption of self-generated electricity power (up to 40%). This conclusion applies to both cases with or without incentives and to any location. If the investment costs of solar-active façade designs would be reduced (a 30% reduction has been here analyzed), the economic attractiveness of the different façade variants would increase, the range of viable configurations would enlarge.

Ackowledgments

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